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Plateauing Cosmic Ray Detectors to Achieve Optimum Operating Voltage

Elissa N. Knoff and Robert S. Peterson

ABSTRACT

Through QuarkNet, students across the country have access to cosmic ray detectors in their high school classrooms. These detectors operate using a scintillator material and a photomultiplier tube (PMT). A data acquisition (DAQ) board counts cosmic ray hits from the counters. Through an online e-Lab, students can analyze and share their data. In order to collect viable data, the PMTs should operate at their plateau voltages. In these plateau ranges, the number of counts per minute remains relatively constant with small changes in PMT voltage. We sought to plateau the counters in the test array and to clarify the plateauing procedure itself. In order to most effectively plateau the counters, the counters should be stacked and programmed to record the number of coincident hits as well as their singles rates. We also changed the threshold value that a signal must exceed in order to record a hit and replateaued the counters. For counter 1, counter 2, and counter 3, we found plateau voltages around 1V. The singles rate plateau was very small, while the coincidence plateau was very long. The plateau voltages corresponded to a singles rate of 700–850 counts per minute. We found very little effect of changing the threshold voltages. Our chosen plateau voltages produced good performance studies on the e-Lab. Keeping in mind the nature of the experiments conducted by the high school students, we recommend a streamlined plateauing process. Because changing the threshold did not drastically affect the plateau voltage or the performance study, students should choose a threshold value, construct plateau graphs, and analyze their data using a performance study. Even if the counters operate slightly off their plateau voltage, they should deliver good performance studies and return reliable results.

Introduction

The QuarkNet project [1] connects high school students to high-energy physics projects and facilitates learning the scientific process [2]. As part of the project, high school students across the world use detectors to gather data about cosmic rays, uploading data to the Cosmic Ray e-Lab [3]. Using the online e-Lab, students further study the data they, and others, have collected [4]. Even schools without detectors can research cosmic rays using the data uploaded by other schools. The detectors utilize technology similar to that used by professional scientists [5]. However, their simplified construction makes them highly usable in a classroom setting. Their primary components include plastic scintillator, photomultiplier tubes [PMTs], a Data Acquisition board (DAQ), and a power distribution unit (PDU) [6]. The PDU delivers a range of 0.3 V to 1.8 V to the PMT. The PMT operates at a voltage 1,000 times that delivered by the PDU (a range of 300 V to 1,800 V). The DAQ coordinates data collection, placing a timestamp on the events detected by the counter [7]. The detector also includes a Global Positioning System (GPS) unit which delivers precise 1-pulse-per-second (1PPS) signals [8]. Students can connect the DAQ board to a computer and use a terminal emulation program such as ZTerm (which was used for this experiment) to view their data [9]. Each participating school receives one DAQ board and the components needed to construct four counters.

Using a terminal emulation program, a user can program the DAQ board to record different types of cosmic ray detections. Students can track the number of cosmic ray "hits" each individual counter receives. They can also utilize the board's coincidence logic to gather data only when a certain number of counters receive a hit [7]. Students can choose to stack counters or arrange them in different configurations to research different properties of cosmic rays. Using the e-Lab, they can perform flux studies to examine the number of cosmic rays passing through their counters in a certain time, look for cosmic ray showers, and investigate muon lifetime [3].

In order to maximize the accuracy of their results, users must minimize background noise while retaining necessary sensitivity to detect the cosmic rays. Users address this issue in two ways: they must determine the appropriate threshold voltage for their counters and they must optimize the voltage the PDU delivers to the PMT [9]. An appropriate threshold voltage allows the detector to recognize real cosmic ray hits while not counting background noise. A correct operating voltage allows the counts recorded to maintain steady even if the PMT tube voltage drifts to either a higher or lower level. In order to achieve optimal operating voltage, users must "plateau" the counters. Each PMT has a different optimum operating voltage that must be determined. In this experiment, we sought to determine the optimum plateau voltage for the counters in the Fermilab Test Array. The Fermilab Test Array is a complete detector set-up that is located on the fifteenth floor of Wilson Hall at Fermilab. QuarkNet staff use this detector for prototyping changes to counters and the DAQ board as well as other non-standard uses. Concurrently, this experiment explored the effects of the threshold setting on the plateau voltage of the counters. This allowed for deeper understanding of the plateau process. Ultimately, we wanted to understand the the plateauing process and to understand how operating at the plateau voltage affects measurements. Through this understanding, we hoped to make the plateauing process more efficient and effective for students and teachers.

Methods and Materials

Detector Setup

For this experiment, we used a complete setup of a cosmic ray detector, which included four counters. Each cosmic ray counter (comprised of a piece of scintillator with a light-channeling "cookie" attached, a PMT, and a base) records the number of cosmic ray hits it receives [9]. As a cosmic ray encounters a scintillator, it produces scintillation light, which is transmitted through the cookie to the PMT. The PMT converts the light signal it receives into an electrical signal [7]. The DAQ board then measures the time that a signal, or pulse, is larger than a certain (user-determined) threshold voltage. This measured time over threshold (TOT) crudely estimates the energy of the incident cosmic ray [9]. The threshold value must be set low enough that the energy of the cosmic rays is "counted" but high enough that background "noise" will not be counted [9].

Determining Optimum Operating Voltage

Each PMT has an optimal operating voltage, which must be determined by plateauing the counters. This step establishes a voltage at which the counter records incoming cosmic rays but little background noise. At the plateau voltage small changes in PMT voltage will not drastically affect the number of cosmic rays recorded by a counter, minimizing the effects of drifts in the tube gain or power supply during the experiment [10]. The plateau voltage is so named because the shape of the graph that plots counts per minute with respect to PMT voltage displays a "plateau" region with approximately equal counts per minute over a range of PMT voltage. Two approaches can be adopted for identifying the plateau region. Plotting the number of counts a single counter receives ("singles rate") with respect to its operating voltage produces a small plateau. The DAQ board can also record the number of coincidence hits ("coincidence rate") between multiple counters. For plateauing purposes, we programmed the DAQ board to respond when two counters received a hit. We kept one counter at a constant voltage while we changed the other counter's (the one being plateaued) voltage. Plotting the coincidence rate with respect to the voltage of the counter being plateaued produced a long, flat plateau [10].

To best determine the operating voltage for a counter, we considered both the singles rate and the coincidence rate [10]. We stacked two counters (for example, counters 1 and 2) so that the same cosmic rays could be tracked as they hit the two counters. To study counter 1, we programmed the DAQ board to record the singles rate for counters 1 and 2, while not recording information from counters 3 and 4. We also programmed the DAQ board to record coincidence rates from a coincident hit on counters 1 and 2 [10]. To make data collection easier, the DAQ board was also programmed to provide counts at one-minute intervals [11]. We recorded all data in terms of PMT voltage (1,000 times the PDU voltage).

To study counter 1, we kept the voltage on counter 2 at a constant, appropriate potential of about 1,000 V. We set counter 1 to a low voltage (600 V–800 V), and we collected at least two data lines (two minutes of data). Using adjacent lines, we subtracted the starting count for channel 1 from the ending count for channel 1 to produce a "total" singles rate. We also used this method for the coincidence rate. This "singles total" as well as the "coincidence total" were recorded. We repeated this process for increasing voltages in 20 V increments, until our singles rates reached approximately 1,200 counts per minute [9]. Our PMTs did not operate effectively with counts higher than this level. When the data were plotted, we explored areas of interest in 10 V increments. Because we cannot operate the PMTs below 300 V, we only plotted values above this voltage.

To determine a good plateau voltage, we plotted the singles rate and the coincidence rate simultaneously with respect to the different PMT voltages. While the singles rate increased, plateaued, and then continued to increase, the coincidence rate increased, plateaued, and did not increase again in the domain of our data. The operating voltage should be located above the "knee" on the singles graph where the graph levels off. The operating voltage should also be located on the plateau of the coincidence graph. Ideally, the PMT setting should be on both plateaus [10]. Furthermore, data from all counters must be considered when determining the correct operating voltages. Each of the four counters should read similar singles rates [11].

Examining the Effects of Threshold

In order to better understand the process of plateauing, we implemented different thresholds and replateaued the counters. We also varied threshold voltages in an attempt to receive consistent singles rates for the four counters. If a counter's plateau voltage corresponded to a higher than expected singles rate, we raised the threshold voltage. If the counter's plateau voltage corresponded to a lower than expected singles rate, we lowered the threshold voltage.

We also adjusted thresholds if a counter was more or less sensitive than the other counters. Particularly for counters that recorded high singles rates at comparatively low operating voltages, we raised the threshold. Similarly, if a counter recorded low singles rates at high operating voltages, we lowered the threshold.

After the counters were plateaued, we then set them at their determined PMT and threshold settings. Data were collected for at least 30 minutes. We then uploaded data to the Cosmic Ray e-Lab [3]. The e-Lab contains different experiments for analyzing data. One experiment, the "performance study" allows groups to evaluate the quality of their data [3]. The e-Lab performs the necessary calculations to deliver a histogram that shows the distribution of the energies of the cosmic rays collected during a data capture. Ideally, the graph should be a Poisson shape [9]. We used these graphs to evaluate choices of operating voltage and threshold.

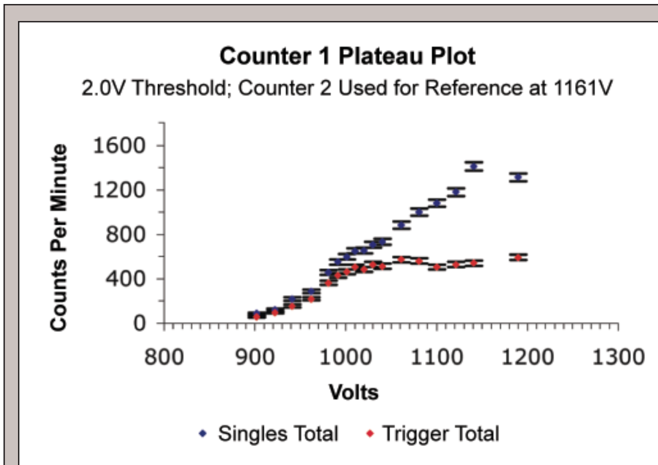

Figure 1. Counts per minute vs. PMT voltage for counter 1 at 2.0 V threshold.

Results

Plateau Voltages for the Counters

Counter 1 was plateaued using counter 2 as a reference for recording coincidence rates. Counter 2 was then plateaued using counter 1 as a reference. We determined the initial threshold and operating voltage for the "reference" by using the standard threshold setting used by classroom teachers and using the operating voltage determined for that PMT by a previous plateauing attempt. The counters exhibited very low count rates until PMT voltages of approximately 900 V were exceeded. Counter 1 showed somewhat defined plateaus on graphs of singles rates with respect to PMT voltage at various threshold voltages. Plateaus for the coincidence rates were longer and more defined. For each threshold voltage, a plateau PMT voltage was chosen to be located on both the singles rate plateau and the coincidence rate plateau. Counter 2 also showed somewhat defined plateaus on the singles rate and more defined coincidence plateaus. Again, we chose a plateau PMT voltage to be located on the plateaus of both the singles graph and the coincidence graph.

We used both counters' graphs to determine the appropriate threshold voltage and PMT voltage combination. We looked for graphs that showed similar singles rates at the chosen plateau voltage. For counters 1 and 2, we chose 2.0 V as the appropriate threshold. 2.0 V gave reasonable (approximately 1 V) plateau voltages and similar singles rates between counters 1 and 2.

Figure 1 shows counts per minute with respect to PMT voltage at a 2.0 V threshold. The coincidence plateau began at around 990 V. The coincidence rate in this plateau region wavered somewhat but remained around 400–500 counts per minute. Using the singles graph, we determined that the plateau voltage was between 1020 V and 1030 V. This range was located above the "knee" on the singles graph where the counts per minute rate began to level off. This range is also located on the long coincidence plateau. In its plateau range, counter 1 recorded singles rates of 710–734 counts per minute.

Figure 2 shows counts per minute with respect to PMT voltage at the 2.0 V threshold. Two small plateaus are visible on the singles rate. The first plateau corresponds to a voltage of 1,100 V–1,120 V.

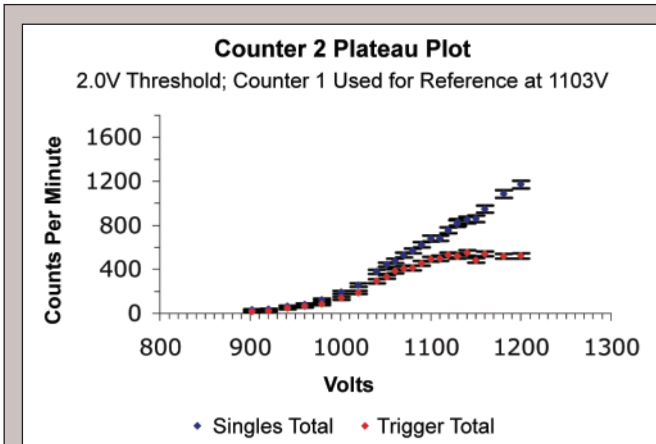

Figure 2. Counts per minute vs. PMT voltage for counter 2 at 2.0 V threshold.

The second plateau corresponds to a voltage of 1,130 V–1,150 V. The long coincidence plateau began at approximately 1,070 V. This plateau had more variation than counter 1's plateau. Again, the coincidence rate ranged from 400–500 counts per minute. We chose the operating PMT voltage to be between 1,100 V and 1,120 V. In this range, counter 2 received 682–757 counts per minute. This plateau corresponded to a more consistent singles rate with counter 1.

Counter 3 and counter 4 were plateaued together in the same manner as counter 1 and counter 2. We used the singles rates we obtained from counters 1 and 2 as reference to judge our data from counters 3 and 4. We looked for plateaus where counters 3 and 4 had singles readings of 700-800 counts per minute.

Counter 3 was more sensitive in that it had higher singles rates at lower PMT voltages. We chose a threshold voltage of 2.5 V so that counter 3 would have a singles rate in the appropriate range at its plateau voltage. Figure 3 shows counter 3's count rate with respect to PMT voltage. Counter 3 showed a small but defined plateau on its singles graph. Again, the coincidence plateau was extended and defined. The coincidence plateau began at 960 V. We determined counter 3's singles plateau to be in the range of 1,000 V–1,020 V.

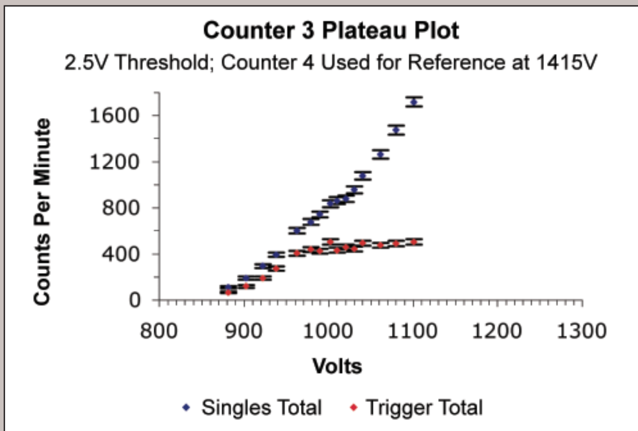

Figure 3. Counts per minute vs. PMT voltage for counter 3 at 2.5 V threshold. Count rates are graphed from 300 V (the lowest voltage to which we can set the PMT).

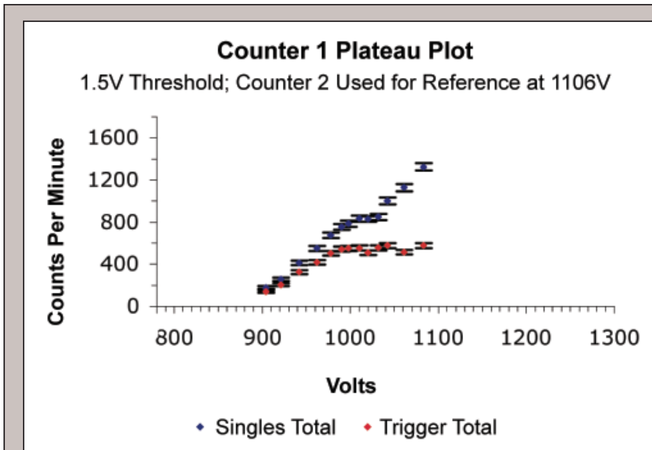

Figure 4. Counts per minute vs. PMT voltage for counter 1 at 1.5 V threshold. Count rates are graphed from 300 V (the lowest voltage to which we can set the PMT).

We chose an operating voltage in this range. Here, the singles rate was between 836 and 839 counts per minute.

Counter 4 exhibited very erratic behavior. Even with a low (1 V–1.5 V) threshold, the PMT voltage needed to be very high (1,400 V–1,500 V) in order to receive comparable singles rates to the other three counters. Furthermore, very small changes in voltage would cause either tremendous increases or drastic decreases in singles rates. We determined that counter 4 was faulty and required repair.

Relationship between Threshold Setting and Plateau Voltage

Figure 4 shows counter 1's plot of counts per minute with respect to voltage at a threshold of 1.5 V. Figure 5 shows counts per minute with respect to voltage for counter 1 at a threshold of 2.8 V. At a 1.5 V threshold, the coincidence plateau began at approximately 980 V. In the plateau, the coincidence values were approximately 500–600 counts per minute. The singles plateau occurred from 1010 V–1030 V. In this range, the singles rate was 834–850 counts per minute. At a 2.8 V threshold, the coincidence plateau began at approximately 1050 V. This plateau had a coincidence rate of 400–440 counts per minute. A small singles plateau occurred from 1070 V–1080 V. Here, the singles rate was 788–801 counts per minute.

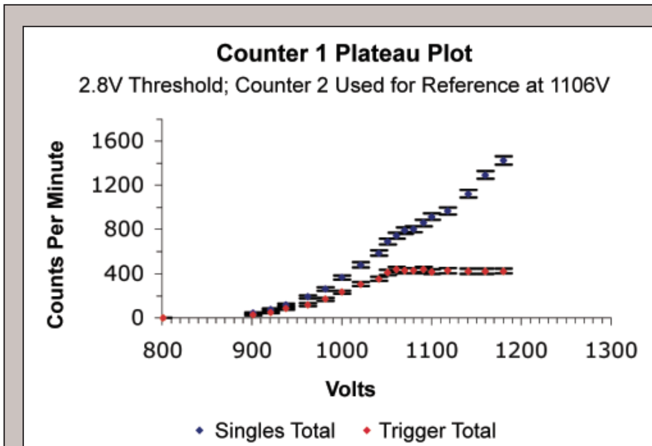

Figure 5. Counts per minute vs. PMT voltage for counter 1 at 2.8 V threshold. Count rates are graphed from 300 V (the lowest voltage to which we can set the PMT).

Discussion and Conclusions

Analyzing Determined Plateau Values

Overall, plateaus were difficult to identify on graphs of singles rates per minute with respect to PMT voltage. Singles plateaus were especially hard to identify given random variations in counts per minute. To determine a rough estimate of this variation, we recorded the singles rates for different one-minute time frames with PMT voltage and threshold voltage remaining constant. In our small sample, we found up to 5 percent variation from our recorded value. This could substantially affect our graphs and the apparent plateaus. Furthermore, the counting error (the square root of each count rate) creates more difficulty in identifying the plateau. As expected, coincidence rate plateaus were very long and easy to identify. The coincidence plateau was not very useful without the singles plateau, however. Because the coincidence plateau was so long, the singles rate varied widely within the plateau range.

Further difficulties arose from uncertainties about the proper singles rate reading for the QuarkNet counters. Adams's guide places the appropriate reading at approximately 300 counts per minute [10]. The user's manual illustrates a plateau value closer to 700–800 counts per minute [9]. This experiment did not find a plateau in the range of 300 counts per minute. In most cases, even the coincidence rate did not plateau in the singles range of 300 counts per minute. Our plateaus were much closer to the 700–800 counts per minute range.

Although our values vary substantially from those prescribed by Adams, our plateau voltages (Table 1) produced good performance graphs (Figure 6). The three counters have very similar counts. Furthermore, their shapes are alike and they have peaks at very similar values. We also tried different combinations of PMT settings and threshold value. Most notably, we tested the counters at the values summarized in Table 2. We chose these values to focus the singles rates more closely at about 800 counts per minute. These settings, however, produced worse performance graphs (Figure 7). These results were somewhat unexpected. We expected that, as long as the chosen plateau value corresponded to the threshold setting, the performance graphs would have the desired Poisson shape. The variation between the two graphs, however, is relatively minor.

Overall, we plateaued the counters effectively. Our singles rates were consistent, and our operating voltages were reasonable. In fact, at thresholds of 1.5 V and 2.5 V, counter 1's plateau corresponded to singles rates closer to 800 counts per minute. This would indicate that the singles rates obtained at the 2.0 V threshold were unusually low. Because these experiments were conducted on different days, this could be due to temporal variation in the number of cosmic rays.

Analyzing the Plateauing Process

Experience with the counters indicates that they deliver consistent count rates during a given time and show very little background noise, especially compared to the well-defined cosmic ray pulses. As shown in Figures 1, 4, and 5, changes in threshold affected the PMT setting but had little effect on the singles rate obtained at the plateau voltage. Even these variations in PMT voltage were fairly small. For use in a classroom, any plateauing procedure must be consistent and efficient. Our experiment indicates that an extremely high level of precision is not necessary to produce good readings from the counters. A good reading in the context of the counters' purpose provides consistency among the counters and leads to a performance graph with only one peak. Keeping this in mind, teachers and students should choose a threshold voltage and produce graphs of counts per minute with respect to PMT voltage. If one counter obtains a widely varying singles rate, i.e. the rate varies by more than 100 or 200 counts per minute, from the other counters, the experimenters can adjust the threshold and re-plateau. The plateauing process is important in that it allows for both elimination of noise and consistent readings. However, since most counter experiments will focus on changes in coincidence rates, the plateauing process should be completed effectively and efficiently.

Counter	PMT Setting (Volts)	Threshold (Volts)
1	1,024	2.0
2	1,114	2.0
3	1,009	2.5

Table 1. Settings for plateaued counters.

Counter	PMT Setting (Volts)	Threshold (Volts)
1	1,023	1.5
2	1,140	2.0
3	1,009	2.5

Table 2. Settings that produce plateaus at singles rates of approximately 800 counts per minute.

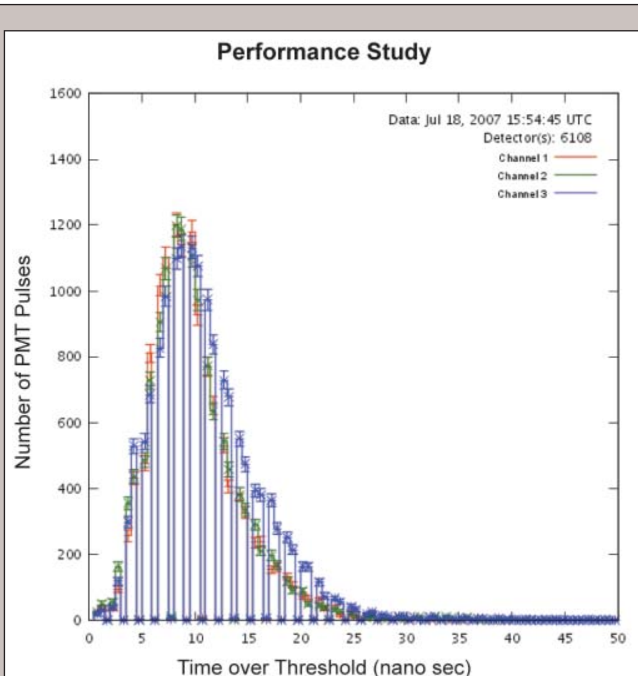

Figure 6. Frequency of pulse lengths for settings in Table 1.

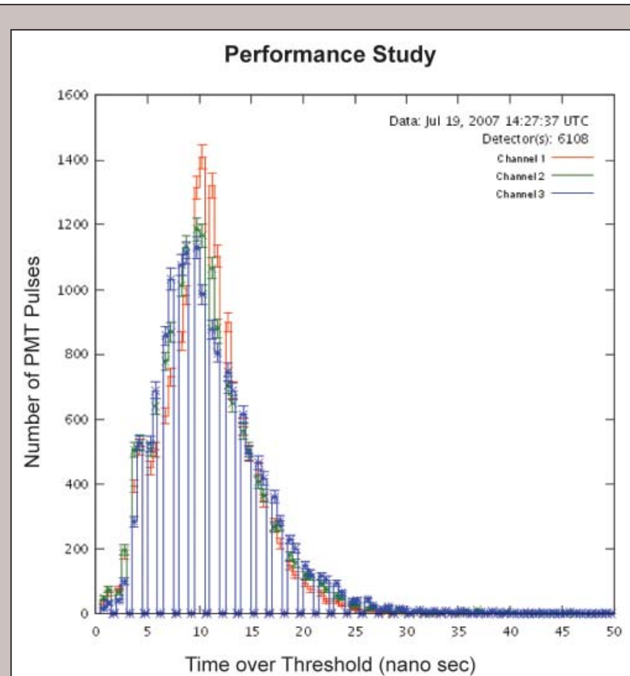

Figure 7. Frequency of pulse lengths for settings in Table 2.

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